6. COMBUSTION

This chapter presents estimates of the net GHG emissions from combustion of each of the materials considered in this analysis and several categories of mixed waste streams (e.g., mixed paper, mixed recyclables, and mixed MSW). Combustion of MSW results in emissions of CO_2 (because nearly all of the carbon in MSW is converted to CO_2) and N_2O. Note that CO_2 from burning biomass sources (such as paper products and yard trimmings) is not counted as a GHG because it is biogenic (as explained in Section 1.4).

Combustion of MSW with energy recovery in a waste-to-energy (WTE) plant also results in *avoided* CO_2 emissions at utility and metals production facilities. First, the electricity produced by a WTE plant displaces electricity that would otherwise be provided by an electric utility power plant. Because most utility power plants burn fossil fuels and thus emit CO_2, the electricity produced by a WTE plant reduces utility CO_2 emissions. These avoided GHG emissions must be subtracted from the GHG emissions associated with combustion of MSW. Second, most MSW combusted with energy recovery in the United States is combusted in WTE plants that recover ferrous metals (e.g., steel) and non-ferrous materials (e.g., non-ferrous metals and glass).[1] The recovered ferrous metals and non-ferrous materials then are recycled.[2] As discussed in Chapter 4, processes using recycled inputs require less energy than processes using virgin inputs. In measuring GHG implications of combustion, one also must account for the change in energy use due to recycling associated with metals recovery.

WTE facilities can be divided into three categories: (1) mass burn, (2) modular, or (3) refuse-derived fuel (RDF). A mass burn facility generates electricity and/or steam from the combustion of mixed MSW. In the United States, about 70 mass burn facilities process approximately 21 million tons of MSW annually.[3] Modular WTE plants generally are smaller than mass burn plants and are prefabricated off-site so that they can be assembled quickly where they are needed. Because of their similarity to mass burn facilities, modular facilities are treated as part of the mass burn category for the purposes of this analysis.

An RDF facility combusts MSW that has undergone varying degrees of processing, from simple removal of bulky and noncombustible items to more complex processes (shredding and material recovery), which result in a finely divided fuel. Processing MSW into RDF yields a more uniform fuel that has a higher heating value than is produced by mass burn or modular WTE.[4] In the United States, approximately 12 facilities process and combust RDF, 7 facilities combust RDF using off-site processing,

[1] We did not consider any recovery of materials from the MSW stream that may occur before MSW is delivered to the combustor. We considered such prior recovery to be unrelated to the combustion operation—unlike recovery of steel from combustor ash, an activity that is an integral part of the operation of many combustors.

[2] Note that material recovery at WTE facilities has increased in recent years, and this trend may continue as more facilities install material recovery systems. According to the Integrated Waste Services Association's *2000 Waste-to-Energy Directory of United States Facilities* (www.wte.org), ferrous metal recovery at WTE facilities increased from more than 773,000 tons in 1999 to more than 788,000 tons in 2000. During the same period, on-site recycling more than doubled, from approximately 462,000 tons to 939,000 tons.

[3] Integrated Waste Services Association, *The 2000 IWSA Waste-To-Energy Directory of United States Facilities*, Table 1. This estimate assumes that 92 percent of combustion system capacity gets utilized, per e-mail correspondence with Maria Zannes of IWSA (June 12, 2001).

[4] MSW processing into RDF involves both manual and mechanical separation to remove materials such as glass and metals that have little or no fuel value.

and 7 facilities process RDF for combustion off-site. These 26 facilities process approximately 8 million tons of MSW annually.[5]

This study analyzed the net GHG emissions from combustion of mixed waste streams, and the following individual materials at mass burn and RDF facilities:

- Aluminum Cans;
- Steel Cans;
- Glass Containers;
- HDPE Plastic;
- LDPE Plastic;
- PET Plastic;
- Corrugated Cardboard;
- Magazines and Third-class Mail;
- Newspaper;
- Office Paper;
- Phonebooks;[6]
- Textbooks;[7]
- Dimensional Lumber;
- Medium-density Fiberboard;
- Food Discards; and
- Yard Trimmings.

Net emissions consist of (1) emissions of non-biogenic CO_2 and N_2O minus (2) avoided GHG emissions from the electric utility sector and from processing with recycled inputs (e.g., steel produced from recycled inputs requires less energy than steel from virgin inputs). There is some evidence that as combustor ash ages, it absorbs CO_2 from the atmosphere. We did not count absorbed CO_2, however, because we estimated the quantity to be less than 0.01 MTCE per ton of MSW combusted.[8] Similarly, the residual waste from processing MSW into RDF is typically landfilled. Some potential exists for the organic fraction of this residual waste to yield GHG emissions when landfilled. We did not count these emissions, however, because the quantity emitted is estimated to be less than 0.01 MTCE per ton of MSW processed into RDF.[9]

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[5] Integrated Waste Services Association, *The 2000 IWSA Waste-To-Energy Directory of United States Facilities*, Table 1.

[6] Newspaper used as proxy, as material-specific data were unavailable.

[7] Office paper used as proxy, as material-specific data were unavailable.

[8] Based on data provided by Dr. Jurgen Vehlow, of the Institut fur Technische Chemie in Karlsruhe, Germany, we estimated that the ash from 1 ton of MSW would absorb roughly 0.004 MTCE of CO_2.

[9] Based on data provided by Karen Harrington, principal planner for the Minnesota Office of Environmental Assistance, we estimated that landfilling the residual waste would emit roughly 0.003 MTCE of CO_2

The results showed that combustion of mixed MSW has small negative net GHG emissions (in absolute terms). Combustion of paper products, dimensional lumber, medium-density fiberboard, food discards, and yard trimmings results in negative net GHG emissions. Processing steel cans at a combustor, followed by recycling the ferrous metal, likewise results in negative net GHG emissions. Combustion of plastic produces positive net GHG emissions, and combustion of aluminum cans and glass results in small positive net GHG emissions. The reasons for each of these results are discussed in the remainder of this chapter.[10]

6.1 METHODOLOGY

The study's general approach was to estimate the (1) gross emissions of CO_2 and N_2O from MSW and RDF combustion (including emissions from transportation of waste to the combustor and ash from the combustor to a landfill) and (2) CO_2 emissions avoided due to displaced electric utility generation and decreased energy requirements for production processes using recycled inputs.[11] To obtain an estimate of the *net* GHG emissions from MSW and RDF combustion, we subtracted the GHG emissions avoided from the direct GHG emissions. We estimated the net GHG emissions from waste combustion per ton of mixed MSW and per ton of each selected material in MSW. The remainder of this section describes how we developed these estimates.

6.1.1 Estimating Direct CO_2 Emissions from MSW Combustion

The carbon in MSW has two distinct origins. Some of it is derived from sustainably harvested biomass (i.e., carbon in plant and animal matter that was converted from CO_2 in the atmosphere through photosynthesis). The remaining carbon in MSW is from non-biomass sources, e.g., plastic and synthetic rubber derived from petroleum.

For reasons described in Section 1.4, this study did not count the biogenic CO_2 emissions from combustion of biomass. On the other hand, we did count CO_2 emissions from combustion of non-biomass components of MSW—plastic, textiles, and rubber. Overall, only a small portion of the total CO_2 emissions from combustion are counted as GHG emissions.

For mixed MSW, we used the simplifying assumptions that (1) all carbon in textiles is non-biomass carbon, i.e., petrochemical-based plastic fibers such as polyester (this is a worst-case assumption); and (2) the category of "rubber and leather" in EPA's MSW characterization report[12] is composed almost entirely of rubber. Based on these assumptions, this study estimated that there are 0.11 pounds of non-biogenic carbon in the plastic, textiles, rubber, and leather contained in 1 pound of mixed MSW.[13] We assumed that 98 percent of this carbon would be converted to CO_2 when the waste is

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per ton of MSW processed into RDF. Facsimile from Karen Harrington, Minnesota Office of Environmental Assistance to ICF Consulting, October 1997.

[10] Note that Exhibits 6-1, 6-2, and 6-5 do not show mixed paper. Mixed paper is shown in the summary exhibit (Exhibit 6-6). The summary values for mixed paper are based on the proportions of the four paper types (newspaper, office paper, corrugated cardboard, and magazines/third-class mail) that comprise the different "mixed paper" definitions.

[11] A comprehensive evaluation also would consider the fate of carbon remaining in combustor ash. Depending on its chemical form, carbon may be aerobically degraded to CO_2, anaerobically degraded to CH_4, or remain in a relatively inert form and be stored. Unless the ash carbon is converted to CH_4 (which we considered to be unlikely), the effect on the net GHG emissions would be very small.

[12] U.S. EPA Office of Solid Waste. 2002. *Municipal Solid Waste in the United States: 2000 Facts and Figures*. EPA 530-R-02-001.

[13] ICF Consulting. 1995. Memorandum. "Work Assignment 239, Task 2: Carbon Sequestration in Landfills," April 28, Exhibit 2-A, column "o."

combusted, with the balance going to the ash. Then we converted the 0.11 pounds of non-biomass carbon per pound of mixed MSW to units of MTCE per ton of mixed MSW combusted. The resulting value for mixed MSW is 0.10 MTCE per ton of mixed MSW combusted,[14] as shown in Exhibit 6-1.

The study estimated that HDPE and LDPE are 84 percent carbon, while PET is 57 percent carbon (based on a moisture content of 2 percent). We assumed that 98 percent of the carbon in the plastic is converted to CO_2 during combustion. The values for CO_2 emissions, converted to units of MTCE per ton of plastic combusted, are shown in column "b" of Exhibit 6-1.

6.1.2 Estimating N_2O Emissions from Combustion of Waste

Studies compiled by the Intergovernmental Panel on Climate Change (IPCC) show that MSW combustion results in measurable emissions of N_2O, a GHG with a high global warming potential (GWP).[15] The IPCC compiled reported ranges of N_2O emissions, per metric ton of waste combusted, from six classifications of MSW combustors. This study averaged the midpoints of each range and converted the units to MTCE of N_2O per short ton of MSW. The resulting estimate is 0.01 MTCE of N_2O emissions per ton of mixed MSW combusted. Because the IPCC did not report N_2O values for combustion of individual components of MSW, we used the 0.01 value not only for mixed MSW, but also as a proxy for all components of MSW, except for aluminum cans, steel cans, glass, HDPE, LDPE, and PET.[16]

6.1.3 Estimating Indirect CO_2 Emissions from Transportation of Waste to the WTE Plant

Next, this study estimated the indirect CO_2 emissions from the transportation of waste. For the indirect CO_2 emissions from transporting waste to the WTE plant, and ash from the WTE plant to a landfill, we used an estimate for mixed MSW developed by Franklin Associates, Ltd. (FAL).[17] We then converted the FAL estimate from pounds of CO_2 per ton of mixed MSW to MTCE per ton of mixed MSW. This resulted in an estimate of 0.01 MTCE of CO_2 emissions from transporting 1 ton of mixed MSW and the resulting ash. We assumed that transportation of any individual material in MSW would use the same amount of energy as transportation of mixed MSW.

6.1.4 Estimating Gross GHG Emissions from Combustion

To estimate the gross GHG emissions per ton of waste combusted, we summed the values for emissions from combustion CO_2, combustion N_2O, and transportation CO_2. The gross GHG emission estimates, for mixed MSW and for each individual material, are shown in column "e" of Exhibit 6-1.

6.1.5 Estimating Utility CO_2 Emissions Avoided

Most WTE plants in the United States produce electricity. Only a few cogenerate electricity and steam. In this analysis, we assumed that the energy recovered with MSW combustion would be in the form of electricity. This analysis is shown in Exhibit 6-2. We used three data elements to estimate the avoided electric utility CO_2 emissions associated with combustion of waste in a WTE plant: (1) the energy

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[14] Note that if we had used a best-case assumption for textiles, i.e., assuming they have no petrochemical-based fibers, the resulting value for mixed MSW would have been 0.09 MTCE per ton of mixed MSW combusted.

[15] Intergovernmental Panel on Climate Change, *Greenhouse Gas Inventory Reference Manual, Volume 3,* (undated) p. 6-33. The GWP of N_2O is 310 times that of CO_2.

[16] This exception was made because at the relatively low combustion temperatures found in MSW combustors, most of the nitrogen in N_2O emissions is derived from the waste, not from the combustion air. Because aluminum and steel cans do not contain nitrogen, we concluded that running these metals through an MSW combustor would not result in N_2O emissions.

[17] Franklin Associates, Ltd. 1994. *The Role of Recycling in Integrated Solid Waste Management to the Year 2000* (Stamford, CT: Keep America Beautiful, Inc.), p. I-24.

Exhibit 6-1
Gross Emissions of GHGs from MSW Combustion (MTCE/Ton)

(a) Material Combusted	(b) Combustion CO_2 Emissions From Non-Biomass Per Ton Combusted	(c) Combustion N_2O Emissions Per Ton Combusted	(d) Transportation CO_2 Emissions Per Ton Combusted	(e) (e = b + c + d) Gross GHG Emissions Per Ton Combusted
Aluminum Cans	0.00	0.00	0.01	0.01
Steel Cans	0.00	0.00	0.01	0.01
Glass	0.00	0.00	0.01	0.01
HDPE	0.76	0.00	0.01	0.77
LDPE	0.76	0.00	0.01	0.77
PET	0.56	0.00	0.01	0.56
Corrugated Cardboard	0.00	0.01	0.01	0.02
Magazines/Third-class Mail	0.00	0.01	0.01	0.02
Newspaper	0.00	0.01	0.01	0.02
Office Paper	0.00	0.01	0.01	0.02
Phonebooks	0.00	0.01	0.01	0.02
Textbooks	0.00	0.01	0.01	0.02
Dimensional Lumber	0.00	0.01	0.01	0.02
Medium-density Fiberboard	0.00	0.01	0.01	0.02
Food Discards	0.00	0.01	0.01	0.02
Yard Trimmings	0.00	0.01	0.01	0.02
Mixed MSW	0.10	0.01	0.01	0.12
Carpet	0.47	0.00	0.01	0.48
Personal Computers	0.75	0.00	0.01	0.76

Note that totals may not add due to rounding, and more digits may be displayed than are significant.
Note that Exhibits 6-1, 6-2, and 6-5 show coated paper but not mixed paper;
mixed paper is shown in the summary exhibit (Exhibit 6-6).
The summary values for mixed paper are based on the proportions of the four paper types (newspaper, office paper, corrugated cardboard, and coated paper) that comprise the different "mixed paper" definitions.
The values for phone books and textbooks are proxies, based on newspaper and office paper, respectively.

Exhibit 6-2
Avoided Utility GHG Emissions from Combustion at Mass Burn and RDF Facilities

(a) Material Combusted	(b) Energy Content (Btu Per Pound)		(c) Energy Content (Million Btu Per Ton)	(d) Mass Burn Combustion System Efficiency (Percent)	(e) RDF Combustion System Efficiency (Percent)	(f) Emission Factor for Utility-Generated Electricity (MTCE/ Million Btu of Electricity Delivered)	(g) (g = c * d * f) Avoided Utility CO_2 Per Ton Combusted at Mass Burn Facilities (MTCE)	(h) (h = c * e * f) Avoided Utility CO_2 Per Ton Combusted at RDF Facilities (MTCE)
Aluminum Cans	-335	a	-0.7	17.8%	16.3%	0.081	-0.01 *	-0.01 *
Steel Cans	-210	a	-0.4	17.8%	16.3%	0.081	-0.01 *	-0.01 *
Glass	-235	a	-0.5	17.8%	16.3%	0.081	-0.01 *	-0.01 *
HDPE	18,687	b	37.4	17.8%	16.3%	0.081	0.54	0.49
LDPE	18,687	b	37.4	17.8%	16.3%	0.081	0.54	0.49
PET	9,702	c,d	19.4	17.8%	16.3%	0.081	0.28	0.25
Corrugated Cardboard	7,043	b	14.1	17.8%	16.3%	0.081	0.20	0.18
Magazines/Third-class Mail	5,258	d	10.5	17.8%	16.3%	0.081	0.15	0.14
Newspaper	7,950	b	15.9	17.8%	16.3%	0.081	0.23	0.21
Office Paper	6,800	b,f	13.6	17.8%	16.3%	0.081	0.20	0.18
Phonebooks	7,950	g	15.9	17.8%	16.3%	0.081	0.23	0.21
Textbooks	6,800	h	13.6	17.8%	16.3%	0.081	0.20	0.18
Dimensional Lumber	8,300	i	16.6	17.8%	16.3%	0.081	0.24	0.22
Medium-density Fiberboard	8,300	i	16.6	17.8%	16.3%	0.081	0.24	0.22
Food Discards	2,370	b	4.7	17.8%	16.3%	0.081	0.07	0.06
Yard Trimmings	2,800	j	5.6	17.8%	16.3%	0.081	0.08	0.07
Mixed MSW**	5,000	k	10.0	17.8%	16.3%	0.081	0.14	0.13

Note that totals may not add due to rounding, and more digits may be displayed than are significant.
* The amount of energy absorbed by 1 ton of steel, aluminum cans, or glass in an MSW combustor would, if not absorbed, result in less than 0.01 MTCEof avoided utility CO2.
** Mixed MSW represents the entire waste stream as disposed of.

a We developed these estimates based on data on the specific heat of aluminum, steel, and glass and calculated the energy required to raise the temperature of aluminum, steel, and glass from ambient temperature to the temperature found in a combustor (about 750° Celsius). We obtained the specific heat data from Incropera, Frank P.and David P. DeWitt, Introduction to Heat Transfer, Second Edition (New York: John Wiley & Sons) 1990, pp. A3-A4.
b MSW Fact Book.
c Gaines and Stodolsky.
d For PET plastic, we converted the value of 9,900 Btu/pound dry weight, to 9,702 Btu/pound wet weight, to account for a moisture content of 2 percent.
e We used Franklin Associates, Ltd.'s value for magazines as a proxy for the value for coated paper.
f We used the MSW Fact Book's value for mixed paper as a proxy for the value for office paper.
g. We used newspapers as a proxy for phonebooks.
h We used office paper as a proxy for textbooks.
i We used the higher end of the Btu factor for Basswood from the USFS. Basswood is a relatively soft wood so its high end Btu content should be most similar to an average factor for all wood types. Fons, W. L.; Clements, H. B.; Elliott, E. R.; George, P. M. 1962. Project Fire Model. Summary Progress Report-II. Period May 1, 1960, to April 30, 1962. Macon, GA: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station, Southern Forest Fire Laboratory. 58 p. [16824]
j Procter and Redfern, Ltd. and ORTECH International.
k Telephone conversation among IWSA, American Ref-Fuel, and ICF Consulting, October 28, 1997.

content of mixed MSW and of each separate waste material considered, (2) the combustion system efficiency in converting energy in MSW to delivered electricity, and (3) the electric utility CO_2 emissions avoided per kilowatt-hour of electricity delivered by WTE plants.

Energy content: For the energy content of mixed MSW, we used a value of 5,000 Btu per pound of mixed MSW combusted, which is a value commonly used in the WTE industry.[18] This estimate is within the range of values (4,500 to 6,500 Btu per pound) reported by FAL[19] and is slightly higher than the 4,800 Btu per pound value reported in EPA's *MSW Fact Book*.[20] For the energy content of RDF, we used a value of 5,700 Btu per pound of RDF combusted.[21] This estimate is within the range of values (4,800 to 6,400 Btu per pound) reported by the DOE's National Renewable Energy Laboratory (NREL).[22] For the energy content of specific materials in MSW, we consulted three sources: (1) EPA's *MSW Fact Book* (a compilation of data from primary sources), (2) a report by Environment Canada,[23] and (3) a report by Argonne National Laboratories.[24] We assume that the energy contents reported in the first two of these sources were for materials with moisture contents typically found for the materials in MSW (the sources implied this but did not explicitly state it). The Argonne study reported energy content on a dry weight basis.

Combustion system efficiency: To estimate the combustion system efficiency of mass burn plants, we used a net value of 550 kilowatt-hours (kwh) generated by mass burn plants per ton of mixed MSW combusted.[25] To estimate the combustion system efficiency of RDF plants, we evaluated three sources: (1) data supplied by an RDF processing facility located in Newport, Minnesota; (2) the Integrated Waste Services Association (IWSA) report *Waste-to-Energy Directory: Year 2000*; and (3) the U.S. Department of Energy's (DOE) National Renewable Energy Laboratory. We used the Newport Processing Facility's reported net value of 572 kwh generated per ton of RDF for two reasons.[26] First,

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[18] Telephone conversation among representatives of Integrated Waste Services Association, American Ref-Fuel, and ICF Consulting, October 28, 1997.

[19] Franklin Associates, Ltd. 1994. *The Role of Recycling in Integrated Solid Waste Management to the Year 2000* (Stamford, CT: Keep America Beautiful, Inc.), pp. 1-16.

[20] U.S. Environmental Protection Agency, Office of Solid Waste. 1995. *MSW Fact Book, Version 2.0* (Washington, D.C.: U.S. Environmental Protection Agency).

[21] Note that this is a value reported by an RDF facility located in Newport, Minnesota; the data were provided by the Minnesota Office of Environmental Assistance. Facsimile from Karen Harrington, Minnesota Office of Environmental Assistance to ICF Consulting, October 1997.

[22] U.S. Department of Energy, National Renewable Energy Laboratory. 1992. *Data Summary of Municipal Solid Waste Management Alternatives Volume IV: Appendix B - RDF Technologies* (Springfield, VA: National Technical Information Service, NREL/TP-431-4988D), p. B-5.

[23] Procter and Redfern, Ltd. and ORTECH International. 1993. *Estimation of the Effects of Various Municipal Waste Management Strategies on Greenhouse Gas Emissions, Part II* (Ottawa, Canada: Environment Canada, Solid Waste Management Division, and Natural Resources Canada, Alternative Energy Division).

[24] Gaines, Linda, and Frank Stodolsky. 1993. *Mandated Recycling Rates: Impacts on Energy Consumption and Municipal Solid Waste Volume* (Argonne, IL: Argonne National Laboratory), pp. 11 and 85.

[25] Note that this is the value reported by Integrated Waste Services Association in its comments to the draft version of the first edition of this report. This value is within the range of values reported by others in response to this draft. Letter received from Maria Zannes, Integrated Waste Services Association, Washington, DC, August 25, 1997.

[26] The net energy value reported accounts for the estimated energy required to process MSW into RDF and the estimated energy consumed by the RDF combustion facility.

this value is within the range of values reported by the other sources. Second, the Newport Processing Facility provided a complete set of data for evaluating the overall system efficiency of RDF plants.[27]

Next, we considered losses in transmission and distribution of electricity. Using a transmission and distribution loss rate of 5 percent,[28] we estimated that 523 kwh are delivered per ton of waste combusted at mass burn facilities, and 544 kwh are delivered per ton of waste input at RDF facilities

We then used the value for the delivered kwhs per ton of waste combusted to derive the implicit combustion system efficiency (i.e., the percentage of energy in the waste that is ultimately delivered in the form of electricity). To determine this efficiency, we first estimated the Btu of MSW needed to deliver 1 kwh of electricity. We divided the Btu per ton of waste by the delivered kwh per ton of waste to obtain the Btu of waste per delivered kwh. The result is 19,200 Btu per kwh for mass burn and 21,000 Btu per kwh for RDF. Next we divided the physical constant for the energy in 1 kwh (3,412 Btu) by the Btu of MSW and RDF needed to deliver 1 kwh, to estimate the total system efficiency at 17.8 percent for mass burn and 16.3 percent for RDF (Exhibit 6-2, columns "d" and "e").[29]

Electric utility carbon emissions avoided: To estimate the avoided utility CO_2 from waste combustion, we used the results in columns "c" and "d," together with a "carbon coefficient" of 0.081 MTCE emitted per million Btu of utility-generated electricity (delivered), based on the national average fossil fuel mix used by utilities[30] as shown in Exhibits 6-3 and 6-4. This approach uses the average fossil fuel mix as a proxy for the fuels displaced at the margin when utility-generated electricity is displaced by electricity from WTE plants. In other words, we assume that nuclear, hydropower, and other non-fossil sources generate electricity at essentially fixed rates; marginal demand is met by fossil sources.[31] The actual carbon reductions could vary depending on which type of fuel used to generate electricity is displaced at the margin. The resulting estimates for utility carbon emissions avoided for each material are shown in columns "g" and "h" of Exhibit 6-2.

6.1.6 Approach to Estimating CO_2 Emissions Avoided Due to Increased Steel Recycling

Next, the study estimated the avoided CO_2 emissions from increased steel recycling made possible by steel recovery from WTE plants for (1) mixed MSW and (2) steel cans. Note that we did not credit increased recycling of non-ferrous materials, because of lack of data on the proportions of those materials being recovered. The result tends to overestimate net GHG emissions from combustion.

For mixed MSW, we estimated the amount of steel recovered per ton of mixed MSW combusted, based on (1) the amount of MSW combusted in the United States, and (2) the amount of steel recovered, post-combustion. Ferrous metals are recovered at approximately 83 WTE facilities in the United States

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[27] The data set included estimates on the composition and amount of MSW delivered to the processing facility, as well as estimates for the heat value of RDF, the amount of energy required to process MSW into RDF, and the amount of energy used to operate the RDF facility.

[28] Personal communication among representatives of Integrated Waste Services Association, American Ref-Fuel, and ICF Consulting, October 28, 1997.

[29] Note that the total system efficiency is the efficiency of translating the energy content of the fuel into the energy content of delivered electricity. The estimated system efficiencies of 17.8 and 16.3 percent reflect losses in (1) converting energy in the fuel into steam, (2) converting energy in steam into electricity, and (3) delivering electricity. The losses in delivering electricity are the transmission and distribution losses, estimated at 5 percent.

[30] Value estimated using data from the Energy Information Administration, *Annual Energy Review 2000* (Washington, DC: U.S. Government Printing Office, DOE/EIA-0384(2000)) August 2001.

[31] Non-fossil sources are expected to meet baseload energy requirements because of the financial incentive for these energy sources to generate at capacity. In general, the marginal cost of producing more power from these sources is minimal compared to the capital costs associated with establishing the facility.

and at seven RDF processing facilities that do not generate power on-site. These facilities recovered a total of nearly 789,000 tons per year of ferrous metals in 2000.[32] By dividing 789,000 tons (total U.S. steel recovery at combustors) by total U.S. combustion of MSW, which is approximately 30 million tons, we estimated that 0.03 tons of steel are recovered per ton of mixed MSW combusted (as a national average).

For steel cans, we first estimated the national average proportion of steel cans entering WTE plants that would be recovered. As noted above, approximately 90 percent of MSW destined for combustion goes to facilities with a ferrous recovery system. At these plants, approximately 98 percent of the steel cans would be recovered. We multiplied these percentages to estimate the weight of steel cans recovered per ton of steel cans combusted—about 0.88 tons per ton.

Finally, to estimate the avoided CO_2 emissions due to increased recycling of steel, we multiplied (1) the weight of steel recovered by (2) the avoided CO_2 emissions per ton of steel recovered. The result was an estimated avoided CO_2 emissions of approximately 0.43 MTCE per ton for steel cans and 0.01 MTCE per ton for mixed MSW, as shown in column "d" of Exhibit 6-5.

[32] Integrated Waste Services Association, *The 2000 IWSA Waste-To-Energy Directory of United States Facilities.*

Exhibit 6-3
Estimating the Emission Factor for Utility-Generated Electricity

	Value	Value	Source
Electric Utility Consumption of Fossil Fuels to Generate Electricity			
Coal (Quadrillion Btu)	17.5		DOE, EIA, "Annual Energy Review: 2000," July 2001, Diagram 5.
Natural Gas (Quadrillion Btu)	3.1		DOE, EIA, "Annual Energy Review: 2000," July 2001, Diagram 5.
Petroleum (Quadrillion Btu)	0.8		DOE, EIA, "Annual Energy Review: 2000," July 2001, Diagram 5.
Total (Quadrillion Btu)	21.4		The sum of coal, natural gas, and petroleum.
Energy Value of one Quadrillion Btu (measured in Kilowatt-hours)	2.9E+11		DOE, EIA, "Form EIA 1605 (1997)," Appendix E.
Total (Billion kwh)	6,268		(21.44 Quad Btu) x (2.92875x10^{11} kWh/Quad Btu) / (10^9 kwh/Billion kwh)
Net Generation: Before Transmission and Distribution Losses (Fossil Fuels Only)			
Coal (Billion kwh)	1,692		DOE, EIA, "Annual Energy Review: 2000," August 2001, Table 8.3.
Natural Gas (Billion kwh)	290		DOE, EIA, "Annual Energy Review: 2000," August 2001, Table 8.3.
Petroleum (Billion kwh)	72		DOE, EIA, "Annual Energy Review: 2000," August 2001, Table 8.3.
Total (Billion kwh)	2,054		The sum of coal, natural gas, and petroleum.
Generation Efficiency (Fossil Fuels Only)			
Generation Output (Billion kwh)	2,054		Calculated above.
Consumption (Billion kwh)	6,268		Calculated above.
Efficiency (Percent)	33%		Generation Output / Consumption, i.e. 2,067 / 6,279.
Efficiency of Energy Conversion From Fossil Fuels to Delivered Electricity			
Transmission and Distribution Losses (TDL) (Percent)	9%		DOE, EIA, "Annual Energy Review: 2000," August 2001, "Electricity Notes."
Delivered Electricity Efficiency (Percent)	91%		Calculated as 100 percent (Deliverable Electricity) - 9 percent (TDL)
Efficiency of Energy Conversion and Delivery for Fossil Fuels (Percent)	30%		Generation Efficiency x Delivered Electricity Efficiency, i.e., 0.33 x 0.91.
Estimated Emission Factor for Delivered Electricity (MTCE/MBtu of Electricity Delivered)			
Weighted Average Emission Factor of the U.S. Mix of Fuels Used to Generate Electricity	**All Fuels**	**Fossil Fuels Only**	
(Kilograms of Carbon in CO_2 per Million Btu Consumed)	16.38	24.04	Exhibit 6-4 of this report.
Weighted Average Emission Factor (MTCE/million Btu)	0.01638	0.02404	Converting kilograms of carbon (kg C) to metric tons of carbon (MTC).
Efficiency of Energy Conversion and Delivery (Percent)	30%	30%	Calculated above.
Emission Factor for Delivered Electricity (MTCE/million Btu)	**0.05493**	**0.08060**	Weighted Average Emission Factor (MTCE/million Btu) / Conversion Efficiency.

Exhibit 6-4
Estimating the Weighted Average Carbon Coefficient of the U.S. Average Mix of Fuels Used to Generate Electricity (MTCE/Million Btu)

Fuel	Net Generation* (Billion kwh)	Percentage of Generation: All Fuels (%)	Percentage of Generation: Fossil Fuels (%)	Carbon Coefficents** (Kg CE Emitted Per Million Btu Consumed)
Coal	1,692	56.1%	82%	25.78
Natural Gas	290	9.6%	14%	14.48
Petroleum***	72	2.4%	4%	21.51
Nuclear	705	23.4%		0
Hydroelectric	253	8.4%		0
Other	2	0.1%		0
Total	3,015	100%	100%	NA
Weighted Average - All Fuels				16.38
Weighted Average - Fossil Fuels				24.04

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

* Source: EIA's *Annual Energy Review: 2000,* "Table 8.3 Electricity Net Generation at Electric Utilities, 1949-2000," for 2000.

** Values include fugitive methane emissions (weighted by the GWP of methane).

*** The carbon coefficient for residual fuel is used as a proxy for petroleum.

Exhibit 6-5
Avoided GHG Emissions Due to Increased Steel Recovery from MSW at WTE Facilities

(a) Material Combusted	(b) Tons of Steel Recovered Per Ton of Waste Combusted (Tons)	(c) Avoided CO_2 Emissions Per Ton of Steel Recovered (MTCE/Ton)	(d) Avoided CO_2 Emissions Per Ton of Waste Combusted (MTCE/Ton)
Aluminum Cans	0.00	0.00	0.00
Steel Cans	0.88	0.49	0.43
Glass	0.00	0.00	0.00
HDPE	0.00	0.00	0.00
LDPE	0.00	0.00	0.00
PET	0.00	0.00	0.00
Corrugated Cardboard	0.00	0.00	0.00
Magazines/Third-class Mail	0.00	0.00	0.00
Newspaper	0.00	0.00	0.00
Office Paper	0.00	0.00	0.00
Phonebooks	0.00	0.00	0.00
Textbooks	0.00	0.00	0.00
Dimensional Lumber	0.00	0.00	0.00
Medium-density Fiberboard	0.00	0.00	0.00
Food Discards	0.00	0.00	0.00
Yard Trimmings	0.00	0.00	0.00
Mixed MSW	0.02	0.49	0.01

Note that totals may not add due to rounding, and more digits may be displayed than are significant.
*The value in column "d" is a national average and is weighted to reflect 98 percent recovery at the 90 percent of facilities that recover ferrous metals.

6.2 RESULTS

The results of this analysis are shown in Exhibit 6-6. The results from the last columns of Exhibits 6-1, the last two columns of Exhibit 6-2, and the last column of Exhibit 6-3 are shown in columns “b” through “e” in Exhibit 6-6. The net GHG emissions from combustion of each material at mass burn and RDF facilities are shown in columns “f” and “g,” respectively. These net values represent the gross GHG emissions (column “b”), minus the avoided GHG emissions (columns “c,” “d,” and “e”). As stated earlier, these estimates of net GHG emissions are expressed for combustion in absolute terms. They are not values relative to some other waste management option. They are expressed in terms of short tons of waste input (i.e., tons of waste prior to processing).

We estimate that combustion of mixed MSW at mass burn and RDF facilities reduces net post-consumer GHG emissions to -0.04 and -0.03 MTCE per ton, respectively. Combustion of paper products has negative net post-consumer GHG emissions ranging from -0.14 to -0.22 MTCE per ton at mass burn facilities and from -0.13 to -0.20 MTCE per ton at RDF facilities. Net GHG emissions are negative because CO_2 emissions from burning paper are not counted (because they are biogenic) and fossil fuel burning by utilities to generate electricity is avoided. Likewise, combustion of medium-density fiberboard and dimensional lumber also results in negative net GHG emissions, with both equaling -0.23 MTCE at mass burn facilities and -0.21 at RDF facilities. Finally, net GHG emissions for food discards and yard trimmings (two other forms of biomass) are also negative, but of a smaller magnitude (-0.05 and -0.07 MTCE per ton of material, respectively, for mass burn and -0.05 and -0.06 MTCE per ton of material, respectively, for RDF).

Combustion of plastics results in substantial net GHG emissions, estimated from 0.21 to 0.27 MTCE per ton of material combusted for mass burn facilities, and from 0.25 to 0.30 MTCE per ton of material input to RDF facilities. This result is primarily because of the high content of non-biomass carbon in plastics. Also, when combustion of plastic results in electricity generation, the utility carbon emissions avoided (due to displaced utility fossil fuel combustion) are much lower than the carbon emissions from the combustion of plastic. This result is largely due to the lower system efficiency of WTE plants, compared with electric utility plants. Recovery of ferrous metals at combustors results in negative net GHG emissions, estimated at -0.42 MTCE per ton of steel cans, due to the increased steel recycling made possible by ferrous metal recovery at WTE plants.

6.3 LIMITATIONS OF THE ANALYSIS

The certainty of the analysis presented in this chapter is limited by the reliability of the various data elements used. The most significant limitations are as follows:

- Combustion system efficiency of WTE plants may be improving. If efficiency improves, more utility CO_2 will be displaced per ton of waste combusted (assuming no change in utility emissions per kwh), and the net GHG emissions from combustion of MSW will decrease.
- Data for the RDF analysis were provided by the Minnesota Office of Environmental Assistance and were obtained from a single RDF processing facility and a separate RDF combustion facility. Research indicates that each RDF processing and combustion facility is different. For example, some RDF combustion facilities may generate steam for sale off-site, which can affect overall system efficiency. In addition, the amount of energy required to process MSW into RDF and the amount of energy used to operate RDF combustion facilities can be difficult to quantify and can vary among facilities on a daily, seasonal, and annual basis. Thus, the values used for the RDF analysis should be interpreted as approximate values.

Exhibit 6-6
Net GHG Emissions from Combustion at WTE Facilities

(a) Material Combusted	(b) Gross GHG Emissions Per Ton Combusted (MTCE/Ton)	(c) Avoided Utility CO_2 Per Ton Combusted at Mass Burn Facilities (MTCE/Ton)	(d) Avoided Utility CO_2 Per Ton Combusted at RDF Facilities (MTCE/Ton)	(e) Avoided CO_2 Emissions Per Ton Combusted Due to Steel Recovery (MTCE/Ton)	(f) (f = b - c - e) Net GHG Emissions from Combustion at Mass Burn Facilities (MTCE/Ton)	(g) (g = b - d- e) Net GHG Emissions from Combustion at RDF Facilities (MTCE/Ton)
Aluminum Cans	0.01	-0.01	-0.01	0.00	0.02	0.02
Steel Cans	0.01	-0.01	-0.01	0.43	-0.42	-0.42
Glass	0.01	-0.01	-0.01	0.00	0.01	0.01
HDPE	0.77	0.54	0.49	0.00	0.23	0.28
LDPE	0.77	0.54	0.49	0.00	0.23	0.28
PET	0.56	0.28	0.25	0.00	0.28	0.31
Corrugated Cardboard	0.02	0.20	0.18	0.00	-0.19	-0.17
Magazines/Third-class Mail	0.02	0.15	0.14	0.00	-0.13	-0.12
Newspaper	0.02	0.23	0.21	0.00	-0.21	-0.19
Office Paper	0.02	0.20	0.18	0.00	-0.18	-0.16
Phonebooks	0.02	0.23	0.21	0.00	-0.21	-0.19
Textbooks	0.02	0.20	0.18	0.00	-0.18	-0.16
Dimensional Lumber	0.02	0.24	0.22	0.00	-0.22	-0.20
Medium-density Fiberboard	0.02	0.24	0.22	0.00	-0.22	-0.20
Yard Trimmings	0.02	0.08	0.07	0.00	-0.06	-0.06
Food Discards	0.02	0.07	0.06	0.00	-0.05	-0.04
Mixed Paper						
Broad Definition	0.02	0.20	0.19	NA	-0.19	-0.17
Residential Definition	0.02	0.20	0.18	NA	-0.18	-0.17
Office Paper Definition	0.02	0.19	0.17	NA	-0.17	-0.15
Mixed MSW	0.12	0.14	0.13	0.01	-0.04	-0.02

Note that totals may not add due to rounding, and more digits may be displayed than are significant.

The reported ranges for N_2O emissions were broad. In some cases the high end of the range was 10 times the low end of the range. Research has indicated that N_2O emissions vary with the type of waste burned. Thus, the average value used for mixed MSW and for all MSW components should be interpreted as an approximate value.

- For mixed MSW, the study assumed that all carbon in textiles is from synthetic fibers derived from petrochemicals (whereas, in fact, some textiles are made from cotton, wool, and other natural fibers). Because we assumed that all carbon in textiles is non-biogenic, we counted all of the CO_2 emissions from combustion of textiles as GHG emissions. This assumption will slightly overstate the net GHG emissions from combustion of mixed MSW, but the magnitude of the error is small because textiles represent only a small fraction of the MSW stream. Similarly, the MSW category of "rubber and leather" contains some biogenic carbon from leather. By not considering this small amount of biogenic carbon, the analysis slightly overstates the GHG emissions from MSW combustion.
- Because the makeup of a given community's mixed MSW may vary from the national average, the energy content also may vary from the national average energy content used in this analysis. For example, MSW from communities with a higher- or lower-than-average recycling rate may have a different energy content, and MSW with more than the average proportion of dry leaves and branches will have a higher energy content.
- In this analysis, we used the national average recovery rate for steel. Where waste is sent to a WTE plant with steel recovery, the net GHG emissions for steel cans will be slightly lower (i.e., more negative). Where waste is sent to a WTE plant without steel recovery, the net GHG emissions for steel cans will be the same as for aluminum cans (i.e., close to zero). We did not credit increased recycling of non-ferrous materials, because of a lack of information on the proportions of those materials. This assumption tends to result in overstated net GHG emissions from combustion.
- This analysis used the national average fossil fuel mix for electricity as the proxy for fuel displaced at the margin when WTE plants displace utility electricity. If some other fuel or mix of fuels is displaced at the margin (e.g., coal), the avoided utility CO_2 would be different (e.g., for coal, the avoided utility CO_2 would be about 0.01 MTCE per ton higher for mixed MSW, and the net GHG emissions would be -0.05 MTCE instead of -0.04 MTCE per ton).

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